COYOTE III:
DEVELOPMENT OF A MODULAR AND HIGHLY MOBILE MICRO ROVER

Roland U. Sonsalla[1], **Joel Bessekon Akpo**[1], **and Frank Kirchner** [1,2]

[1]*DFKI Robotics Innovation Center, Robert-Hooke-Str. 1, 28359 Bremen, Germany, Email: Roland.Sonsalla@dfki.de, Joel.Bessekon_Akpo@dfki.de, Frank.Kirchner@dfki.de*
[2]*University of Bremen, Robotics Lab, Robert-Hooke-Str. 1, 28359 Bremen, Germany*

ABSTRACT

Robotic exploration missions are gaining in importance for the exploration of our solar system. A wide range of different scientific goals have been formulated for future exploration of Moon and Mars. In order to achieve these goals a need arises for robotic systems and mission set-ups with increasing complexity. Coyote III is developed within the scope of the project TransTerrA, which aims to implement a logistics chain to handle complex mission tasks. Within this paper the design considerations for Coyote III as well as the development and overall modularity concept, including a modular manipulation device, are presented. Coyote III is a highly mobile modular micro rover platform, able to act as a shuttle rover performing autonomous operations.

Key words: Micro Rover, Manipulator, High Mobility, Modularity.

1. INTRODUCTION

Future exploration of the solar system is calling for robotic missions with increasing complexity. Scientific concepts for the exploration of Moon and Mars ask for advanced instrumentation and experiments such as sample acquisition and return, while pushing into more hostile environments [1]. These missions get increasingly difficult to handle with common rover architectures but call for combining multiple, specialized exploration vehicles. A first attempt in this direction is, e.g., the proposed ESA/NASA Mars Sample Return mission, including one rover for taking samples and a second rover for fetching these samples for the the sample return stage [2].

Within this paper, the development of the Coyote III terrestrial rover testbed as shown in Figure 1 is presented. With a total mass of 12.5 kg and boundary-box dimensions of $994 \times 584 \times 380$ mm Coyote III can be considered as a micro rover. It is specially designed to be used as a highly mobile modular rover platform able to perform autonomous operations. Coyote III is developed within the scope of the project TransTerrA, which aims to implement a logistics chain based on a variety of various robotic systems. It is proposed to operate as a shuttle system within the logistics chain, cooperating with a primary exploration rover as well as different stationary and portable robotic devices.

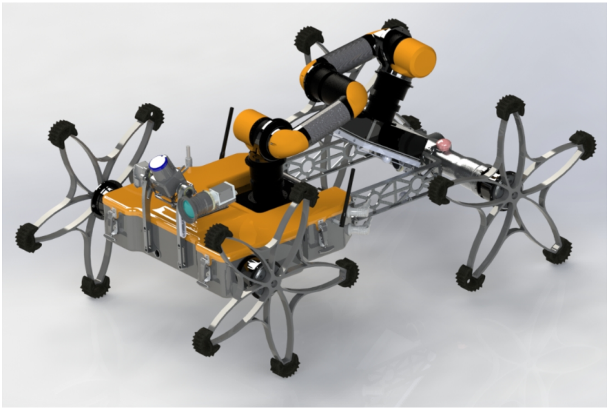


Figure 1. CAD model of Coyote III equipped with its manipulation device

A focus is given on the design considerations of Coyote III. These are based on the lessons learned form the Coyote II development and field trials as well as specific requirements based on the reference mission scenario. An outline of the reference mission concept is given in Section 2. Within Section 3 the general development concept and design consideration of Coyote III are presented. To enable Coyote III to perform as shuttle rover within the aforementioned logistics chain, it needs to be able to carry and handle standardized payload items (PLI). Therefore, Coyote III will be equipped with two electromechanical interfaces (EMI) allowing to dock PLIs to the rover and add a modular manipulation device to the system as shown in Figure 1. Within Section 4 the modularity concept for Coyote III is lined out. Furthermore, the manipulator is conceptualized and introduced. Section 5 includes a system overview of Coyote III as well as an introduction of its different subsystems. A conclusion and outlook is given in Section 6.

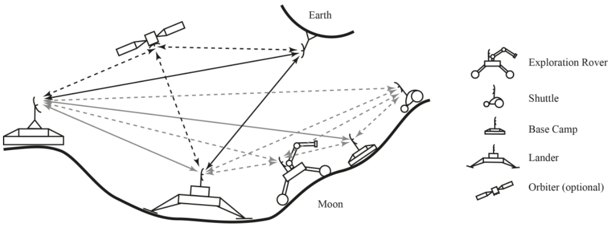


Figure 2. Schematic drawing of the implementation of a logistics chain using a heterogeneous team of mobile and stationary robots (arrows represent possible communication links)

2. REFERENCE MISSION CONCEPT OUTLINE

The mission design concept is motivated by the need of robotic systems able to handle exploration tasks with increasing complexity. This includes e.g. (multi-) sample return missions as well as tasks in the field of resource utilization and even the preparation of (long term) manned missions. The project TransTerrA envisages to extend the exploration capabilities and handle complex mission tasks in a (semi-)autonomous manner by introducing a semi-autonomous and heterogeneous team of cooperating mobile robots, able to establish a logistics chain. The general idea of implementing a logistics chain including various robotic systems is depicted in Figure 2. An exploration rover is paired with one or more small supporting rovers (shuttles) building up a logistics chain between the rover and the lander via stationary elements (base camps).

For the reference mission scenario the robotic systems are designated to operate inside Amundsen crater, located close to the lunar south pole. This landing site was chosen based on a trade-off between different scientific goals for lunar exploration, as identified in [3, 4]. The primary scientific objective within Amundsen crater is to study volatiles and their flux in the lunar pole regions. Due to its location and crater diameter of approximately 150 km, only some parts of the crater are in permanently shadowed regions (PSR), such that the robots could be deployed in a sunlit region on the flat crater floor.

A landing site at 83.82° S, 87.53° E as shown in Figure 3 is proposed for the reference mission. The surface exploration would than start on two exploration legs, aiming for the points of interest (b1 - b7) as indicated in Figure 3. The first exploration leg is heading towards the central peak of Amundsen crater covering b1 & b2 and requiring the ability of the rovers to move in soft soils (regolith) and on slopes with up to 15° inclination. The second exploration leg is designated to enter PSR in the direction of the outer crater wall and point b7. Both legs contain sample acquisition in order to study ancient regolith processes as well as trapped volatiles within the soil. These samples would be stored within sample containers which need to be delivered back to a sample return stage utilizing the logistic chain.

Following the depicted exploration scenario, the exploration rover needs to travel a total distance of approximately 47.75 km with a maximum distance from the landing site of 20 km, and 3915 m of cumulative elevation gain. Within the mission concept the exploration rover is the primary mobile element. It serves as main exploration device, able to conduct the major mission tasks and serves for transport and deployment of base camps.

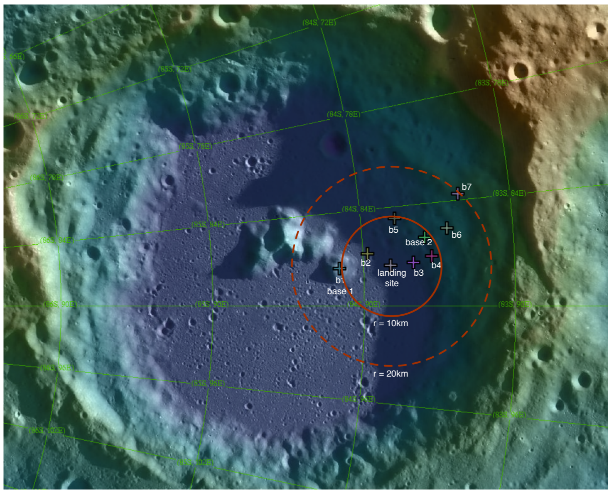


Figure 3. Multi-level surface map with a satellite mosaic overlay [5] of Amundsen Crater with highlighted landing site and points of interest (b1 - b7)

The exploration rover is paired up with at least one shuttle rover. The shuttle is a compact, highly mobile system and the core element for establishing a supply chain between stationary infrastructure elements - such as lander and/or sample return stage, base camps and the exploration rover. The base camps are stationary elements providing infrastructure to support the logistics chain. They can serve as junction point as shown in Figure 2 to exchange, e.g., PLIs between the different systems. Further functionality for energy harvesting, communication or scientific instrumentation may also be provided by base camps depending on the needs of the mission.

This reference mission set-up provides the basis for terrestrial implementations and tests of the different robotic systems, performing logistics chain applications. While this paper focuses on the development of Coyote III which will be used as shuttle rover, a more detailed description of the reference mission concept and the different robotic elements is given in [6].

3. COYOTE III DESIGN CONSIDERATIONS, CONCEPT AND DEVELOPMENT

Following the reference mission scenario some generic top level requirements have been identified for the capabilities of the terrestrial testbed Coyote III. Acting as a shuttle rover it has to be able to quickly cover rough terrain. Its main task is carrying PLIs between stationary nodes and the exploration rover, thus keeping the logistics chain active. With respect to a multi rover mission scenario, the shuttle rover should be as small and lightweight as possible, keeping the impact on the launch mass and volume at a minimum. Furthermore, it needs to be able to operate with a high level of autonomy in order to reduce the additional mission control activities.

As a sum up, the following needs respective to the top-level requirements were taken into account for the Coyote III conceptualisation and development:

- (Semi-) Autonomous operation within the logistics chain
  - Cooperation with other mobile robots (exploration rover)
  - Cooperation with stationary units (lander and/or base camps)
  - Cooperation with modular elements (PLIs)
- High mobility within unstructured terrain
- Carrying and handling of PLIs
- Small and lightweight rover system

Coyote III is a direct advancement of the Coyote II rover. Coyote II was developed within the vicinity of a multi rover scenario as well, acting as a small scout rover with the aim to improve the mission safety and the effective traverse speed for planetary rover exploration as part of the FASTER project. Therefore, Coyote II was equipped with a set of different soil sensors, able to provide suitable information on the terrain ahead of a primary exploration rover to avoid uncertain estimations concerning the trafficability of the areas to be traversed (c.f. [7, 8]). Coyote II was successfully tested within various laboratory tests and field trials at DFKI RIC, Bremen, University of Surrey and Airbus Defence and Space (DS), Stevenage. A full dual rover system proof of concept trial has been conducted within the Mars Yard at Airbus DS in Stevenage, applying the ExoMars breadboard BRIDGET as primary rover [9].

One of the main drivers for the Coyote II development was to provide high mobility performance in rough rocky terrain as well as soft soils while avoiding creating obstacles for the following rover by disturbing the soil. Therefore, Coyote II was equipped with two hybrid legged-wheels in the front and two spherical helical wheels in the rear. This set-up allows performing side-to-side steering manoeuvres, reducing the soil disturbance during point turns and smooth continuous driving. Coyote II gained a heigh overall mobility with this set-up. During various mobility test campaigns and full system tests on different regolith and Mars soil simulants it could however be observed, that a wheel configuration with four hybrid legged-wheels outperforms the chosen Coyote II set-up in terms of step climbing, crevasse traversing and steep inclination drives [8, 10]. The soil disturbance and rover bouncing is however higher by using four hybrid legged-wheels without proper foot placement control (c.f. [11]). Observations of locomotion tests on regolith simulant (basalt split $\sim 500\,\mu m$) and martian soil simulant (2EW quarz based sand $\sim 500\,\mu m$) demonstrated that the side to side movement of the spherical helical wheels can be highly dependent on the soil parameters. While the helical wheels performed their side movement within the basalt split very well, they could not gain a lot of sideways thrust within the 2EW soil. Based on these observations the locomotion system of Coyote III was depicted to be equipped with four hybrid legged-wheels, as commonly used for numerous rovers of the Asguard family.

Figure 4. Coyote III in its current state, standing on a steep rocky slope

The Coyote III rover is shown in Figure 4, representing its current state. The design of Coyote III is based on lightweight construction using carbon fibre reinforced plastic (CFRP) paired with lightweight aluminium structures. While it is not fully equipped for the proposed later on multi robot test campaigns in its current state, the current rover platform gains a mass of 12.5 kg. Its main dimensions are: 994 mm × 584 mm × 380 mm (l×w×h). Other than Coyote II, Coyote III is designed and build following a modular design concept which reflects within the general rover platform design. As indicated in Figure 5 the Coyote III platform can be divided into five major sub-assemblies which are described in more detail within the following paragraphs. A general system and subsystem overview is given in Section 5.

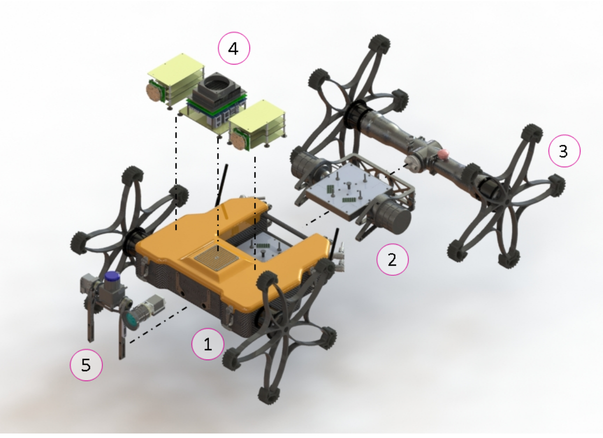


Figure 5. Exploded view of Coyote III showing its main sub-assemblies

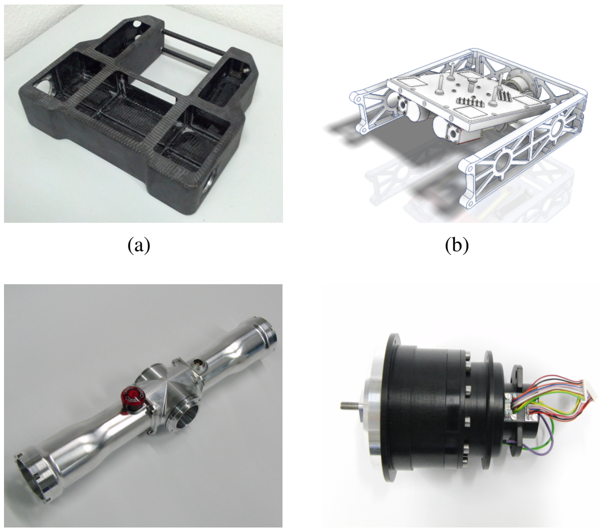
1. Front Body

The front body includes the main housing of Coyote III, as well as the driving units of the front wheels. Based on the gained experience from Coyote II, the mechanical structure of Coyote III was designed to reach an improved volume to mass ratio. Therefore, its main housing, shown in Figure 6(a), is constructed out of laminated CFRP. The main housing is designed in a U-shape with boundary box dimensions of 355 mm × 410 mm × 108 mm (l × w × h), comprising an 167 × 165 mm payload bay between both limbs. The hatch dimensions are chosen to allow the installation of an EMI within the payload bay, as needed for shuttle operations of Coyote III.

Due to its complex geometry the housing was designed and manufactured as semi-monocoque construction. To improve the stability and statics of the monocoque, waterjet cutted CFRP sheets have been inserted as ribbings. Additional aluminium mounts and inserts have been attached to the CFRP housing to serve as mount points for the front driving units as well as the centre body and the subsystem compartments. Strong aluminium mounts able to carry the whole rover weight have been inserted at each side of the payload bay in order to provide connection points for additional payload. The implementation of payload modules and/or an EMI, as proposed for shuttle applications, additionally improves the mechanical stability of the main housing.

A cut-out provides direct access from the payload bay to the front sections for cable routings. Additionally the main housing is equipped with mounting points and cable bushings in the front, allowing to, e.g., connect a sensor bench to the rover. In order to provide communications and power supply to the centre and rear body, four connector ports are placed at the back of the main housing (c.f. Figure 6(a)).

The bottom of the front body provides two (35 × 30 mm) cut-outs with mount-points, allowing to install additional sensors to the rover, such as cameras facing the ground



(a) (b)

(c) (d)

Figure 6. Mechanical parts and elements of Coyote IIIs sub-assemblies: a) pre-finished main housing, b) proposed center body with 2 DoF EMI platform, c) rear body structure, d) actuator module

or the wheels. A thin stainless steel sheet was added to the bottom as well, providing under-body protection in rough and unstructured terrain. Overall, including all attachment-points, such as mounts, mechanical connectors and the under-body guard as well as the CFRP laminated top cover the main housing gains a mass of 2.1 kg.

Directly attached to the main housing are two front driving units as shown in Figure 6(d), allowing to individually actuate each front wheel. The motor module is based on a BLDC motor paired with an harmonic drive gear gaining a stall torque of 72 Nm and a mass of 0.7 kg. It is equipped with two absolute encoders (input and output side) allowing to apply motor commutation as well as direct control at the output shaft.

2. Centre Body

The centre body is based on lightweight aluminium frame design. It contains basically three framework elements, two side elements, connecting to the front body and a rear element providing an assembly flange to the rear body as illustrated in Figure 6(b). The centre body is designated to serve as mounting point for additional payload to Coyote III as well. It can be easily adapted to meet special requirements for payload mounting or even to change the geometry of the rovers chassis, e.g., for mounting two different wheel types in the front and rear such as applied on Coyote II. In order to change the shape of the centre body the two side beams can be replaced to meet the current needs. This is possible as the centre body can be treated independently from the front and rear body. Two connector ports at the front body are reserved for communication and power supply to the centre body. Each of this connectors can be equipped with up to 19 contacts.

Within the TransTerrA set-up the centre body will be equipped with a passive EMI as docking-point for further subsystems such as PLI or the robotic-manipulator (c.f. Section 4). It is envisaged to place the EMI on an active two degree of freedom (DoF) platform, able to perform movements in roll and pitch direction in a range of -10° to +30° as sketched in Figure 6(b). The platform allows to extend the workspace of the manipulator, e.g., for a compact stowage position or for improved manipulation capabilities while interacting with a base camp. Furthermore, it provides a movable docking point for PLIs, allowing to, e.g., perform pointing manoeuvres when required.

Currently Coyte III is equipped with a preliminary centre body gaining a mass of 0.6 kg as shown in Figure 4. It provides mounting points on each side. The shape is specially designed to allow a proper rover pose for the attachment of two spherical helical wheels (with smaller diameter) as well as two hybrid legged-wheels in the rear.

3. Rear Body

The rear body is a 3D-milled aluminium structure based on a centre T-link and two tube-like extensions for connecting the rear driving units (cf. Figure 6(c) and 6(d)). The T-link connects to the centre body and has an integrated roll joint with a rotation range of $\pm 20°$. This allows to tilt the whole rear axis in order to keep ground contact with all four wheels while driving over rough terrain. An absolute encoder is integrated within the roll-joint to track the pose of the rovers chassis. A similar combination of the roll-joint based chassis and the hybrid legged-wheels has been applied to the rovers of the Asguard family as well as to Coyote II [8, 10]. All rovers showed a remarkable high mobility performance.

4. Subsystem Compartments

The subsystem compartments of Coyote III are placed within the front bodies main housing. They are designed in an adaptable stack-architecture which is mounted to aluminium connectors, placed within the main housing. The stack-architecture allows adopting and/or extending the subsystems board-wise if required. The subsystems currently integrated in Coyote III's subsystem compartments are given in Section 5.

5. Sensor Bench

The sensor bench is connected to the front body and is currently equipped with two optical sensors (c.f. Section 5). It contains a camera and a laser range finder which is mounted on an actively tiltable platform. With a range of rotation of $\pm 180°$ it is possible to perform sweeping movements with the laser range finder in all directions. The sensor set-up allows to perform simultaneous localisation and mapping tasks on-board Coyote III, enabling it to run fully autonomous traversals and/or operations.

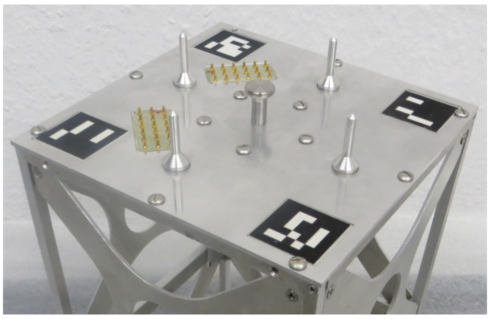


Figure 7. Passive EMI attached to PLI core structure (PLI baseline dimensions: 154×154×150 mm)

4. MODULARITY CONCEPT

Coyote III is designated to work as a shuttle rover within a heterogeneous team of robots in order to build up a logistics chain. Following the previously described reference mission, it is intended to perform demonstration scenarios in terrestrial test facilities. Besides the shuttle system SherpaTT [12] will be used as second mobile robotic element, acting as the primary exploration rover. The two rovers will be accompanied by stationary base camps which can be deployed by SherpaTT and portable payload items able to be docked to each of the different systems [6]. A core element of the modularity concept regarding the cooperation of the different robotic elements, is a standardized docking interface, allowing to establish a logistics chain. An improved version of the docking mechanism presented in [13] will be applied to all robotic elements, acting as EMI. The EMI consists of an active and a passive part. While the passive parts contains four guiding pins, a central locking bolt, spring seated electronic connection pins and optical markers, as shown in Figure 7, the active side contains the locking mechanism as well as a camera module for vision based docking control and PLI management electronics.

Coyote III will be equipped with two passive EMIs, one placed within its front body payload bay and a second one on a roll-pitch platform within the centre body (c.f. Section 3). This EMIs allow to dock modular payload elements like PLI to the rover. In order to manage the various modular payload elements and integrate them into Coyote III's logic, the rover will be equipped with its own payload management system (PMS). Specially the fixed EMI within the front body is designated to serve as docking point and/or for the transport of PLI within the envisaged logistics chain. The movable EMI, placed at the centre body, can be used for this purposes as well, while it is designated as primer docking point for a modular ma-

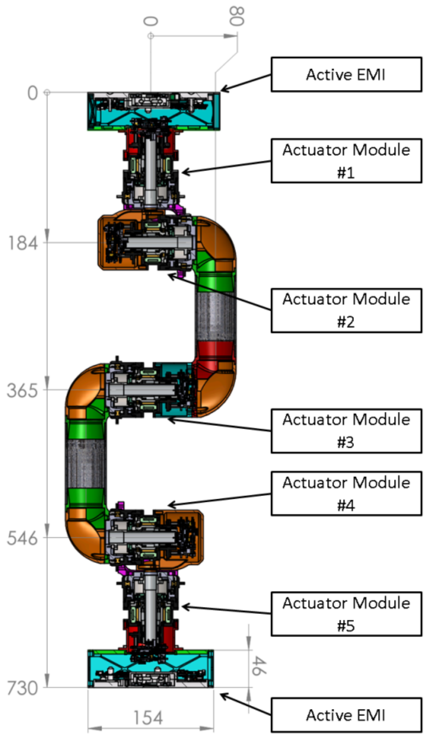


Figure 8. Proposed modular 5 DoF manipulator for PLI handling

nipulator payload delivery system (MPDS) as shown in Figure 1.

One of the main aspects of the modularity concept throughout the envisaged logistics chain is is based on the transportation of PLIs. They can be equipped with various functionality, such as, e.g., additional power packs, sampling tools and container, or stand alone instruments for either stationary measurements or for a functional extension of a robotic system such as the exploration or shuttle rover or the base camps.

In order run as a shuttle rover Coyote III needs to be able to handle the PLIs it is transporting. For the purpose of this task a 5 DoF robotic-arm as shown in Figure 8 has been developed. One of the key features is its symmetrical design including an active EMI on each endeffector sides. This allows to dock the manipulator to Coyote III via an EMI and act as MPDS. Furthermore, the symmetrical configuration allows a wide range of capabilities such as switching positions on both payload bays or fully undock from the shuttle rover and bridge over to the exploration rover or to one of the base camps. With this set-up it is fully integrated into the modularity concept envisioned for the logistics chain.

The manipulator is based on three main subsystems: the EMIs, the actuator modules and the supporting link structure. The EMIs are each equipped with an integrated communication and power management board, managing the power and communication to the actuator modules as well as for potentially docked PLIs. The same type of

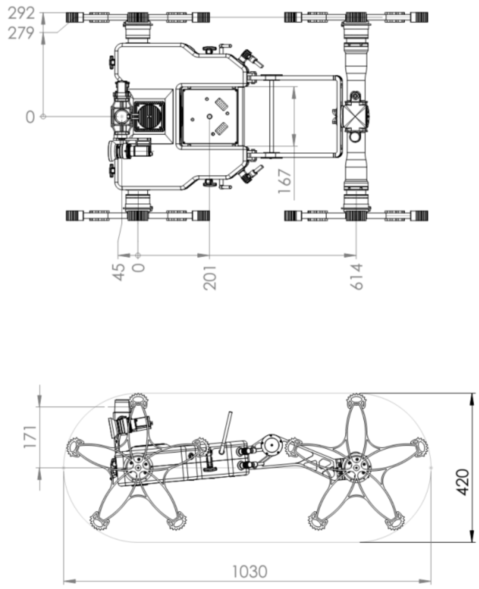


Figure 9. Main dimensions of Coyote III

actuator modules as used as driving units for Coyote III are applied as manipulator joints (c.f. Section 5). Due to the symmetrical design and operation purposes of the manipulator, each joint is equipped with a Robodrive ILM 50×14 bldc-motor paired with a Harmonic Drive gear at a reduction ratio of 160:1, gaining a nominal torque of 80 Nm (224 Nm stall torque). Each actuator module is equipped with its own FPGA based motor driver, as used in Coyote III as well. The link structure is based on lightweight aluminium connectors and CFRP tubes.

The MPDS is designed to be able to handle a payload of up to 5 kg. Fully stretched out the arm reaches a length of 730 mm as shown in Figure 8. The total mass of the manipulator is estimated to be 6.5 kg, as the device is still under development.

5. COYOTE III SYSTEM OVERVIEW

The current state of Coyote III is shown in Figure 4. An overview of its main dimensions and/or boundary box is given in Figure 9. A technical overview of the rover platform and its subsystems can be found in Table 1. The rover system bus is fully integrated and has performed its initial operation runs. It includes all main subsystems, namely:

- Structure and Mechanisms (StM)
- On-Board Data Handling (OBDH)
- Communications (COM)
- Electrical Power Supply (EPS)
- Thermal Control Management (TCM)

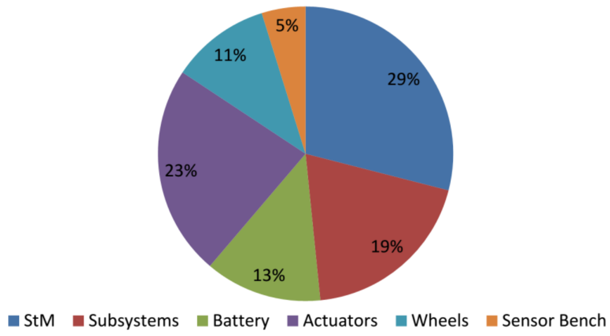


Figure 10. Coyote III mass distribution

- Navigation Sensor System (NSS)

The overall rover platform gains a mass of 12.5 kg which is distributed as shown in Figure 10. It has to be noted that neither the proposed two EMIs with their mountings nor any additional payload like PLIs and/or MPDS are included within the mass budget and distribution. The extension of Coyote III with its payload subsystems is still under development. This includes the following subsystems in particular:

- Payload Management System (PMS)
- Electro-Mechanical Interface (EMI)
- Manipulation Payload Delivery System (MPDS)

While the MPDS can be seen as optional payload, the PMS and EMI will add an additional mass of approximately 2 kg to the rover platform. The overall mass of the fully equipped shuttle system Coyote III as show in Figure 1 is estimated to reach about 21 kg with the capability of loading an additional 5 kg PLI.

6. CONCLUSION AND OUTLOOK

The development of the modular and highly mobile micro rover Coyote III was presented within the previous sections. Coyote III is developed within the scope of the project TransTerrA which aims to implement a logistics chain, based on an heterogeneous team of mobile and stationary robotic devices. While Coyote III is designed to be used as a modular rover platform, it is envisaged to operate as shuttle rover within the logistics chain. Based on a reference scenario placed within Amundsen crater at the lunar south pole, a set of top-level requirements has been derived for the conceptualization and development of Coyote III.

Coyote III represents an enhanced design of the Coyote II rover, which was successfully tested and operated as micro scout rover. The design considerations and development concept of Coyote III is directly derived from the lessons learned of Coyote II as well as the given reference mission scenario. A modular design concept based on lightweight construction was chosen for Coyote III allowing to implement additional payload elements. Following the modularity concept introduced by the logistics chain, Coyote III is envisaged to be equipped with two EMIs. They allow to dock additional PLI to the rover and provide the potential of extending the functionality of the rover platform. For PLI handling, a modular MPDS has been developed, which can be docked to Coyote III via its EMIs. Due to its symmetrical design it is not limited to one home system but can be fully integrated into the modularity concept envisioned for the logistics chain.

Table 1. System parameters of Coyote III

Structure and Mechanisms	
Size (l $\times$ w $\times$ h):	994 $\times$ 584 $\times$ 380 mm
Mass:	12.5 kg
4-Wheel drive:	Robodrive ILM 50$\times$08 bldc-motor, Harmonic Drive gearing (80:1)
Wheel torque:	nominal 22.4 Nm
Speed:	max. 1.3 m/s
Cassis:	Passive roll joint at rear axis
Wheels:	Hybrid legged-wheels
Housing:	CFRP housing paired with aluminium structures
On-Board Data Handling	
On-board computer	IntelCore i7-3517UE, 1.7 GHz
Motor control	Distributed FPGA based control
Communications	
Mobile access point:	2.4 GHz, 802.11n
Remote control:	Bluetooth
Remote stop:	868 MHz XBee-PRO
Power Supply	
Power supply:	LiPo primary battery (44.4 V, 4.5 Ah) external power supply (optional)
Main bus:	*44.4 Vdc*
Motor bus:	*44.4 Vdc*
Subsystem bus:	*12.0 Vdc and 5.0 Vdc*
Power consumption:	$\sim$ 75 W (driving, average)
Thermal Control	
Front compartments:	Active control with health monitoring
Driving units:	Passive control with health monitoring
Navigation Sensor System	
Laser range finder:	Hokuyo UST-20LX (tiltable by $\pm 180°$)
Camera:	Basler Ace acA2040-25gc, 2048$\times$2048 px. 25fps, FoV: 79.7° horizontal
IMU:	Xsens MTi-300 AHRS
Embodied sensors:	Absolute encoders at body joint and driving units, wheel torque measurement

Currently Coyote III is equipped with all rover-bus subsystems and has successfully performed its initial operation runs. The payload related subsystems such as PMS, EMI and MPDS are still under development but will be integrated to the rover platform in the near future. Different test campaigns ranging from locomotion performance tests to autonomous cooperative tasks within a multi robot set-up are planned and will be carried out in the future.

In parallel to the further development of Coyote III with respect to the space related reference scenario, potential transfer applications for terrestrial operations are investigated. As a major field of interest the search and rescue domain was identified. An adequate sensor set-up for such applications is under development. Furthermore, applicable operation and test scenarios, including various parts of the logistics chain, have been specified and are envisaged to be tested in the future as well.

ACKNOWLEDGMENTS

The authors would like to thank the TransTerrA team and all supporting staff at DFKI Robotics Innovation Center Bremen. The work presented is part of the project TransTerrA which is funded by the German Space Agency (DLR Agentur) with federal funds of the Federal Ministry of Economics and Technology in accordance with the parliamentary resolution of the German Parliament, grant no. 50 RA 1301.

The development and tests of the rover system Coyote II was part of the already finished Forward Acquisition of Soil and Terrain Data for Exploration Rover (FASTER) project, funded by the EU FP7 program under grant no. 284419.

REFERENCES

[1] International Space Exploration Coordination Group (ISECG). *The Gloabl Exploration Roadmap*, August 2013.

[2] Erik Nilsen, Charles Whetsel, and Richard Mattingly. Mars sample return campaign status. In *Proceedings of the 2012 IEEE Aerospace Conference*, pages 1–7, Big Sky, MT, March 2012.

[3] David A. Kring and Daniel D. Durda, editors. *A Global Lunar Landing Site Study to Provide the Scientific Context for Exploration of the Moon*. LPI-JSC Center for Lunar Science and Exploration, 2012. LPI Contribution No. 1694.

[4] George A. Paulikas, Carle M. Pieters, Lennard A. Fisk, and A. Thomas Young, editors. *The Scientific Context for Exploration of the Moon: Final Report*. National Academies Press, Washington, D.C., 2007.

[5] LROC-Team. Lroc quickmap tool. http://target.lroc.asu.edu/q3/, August 2013.

[6] Roland U. Sonsalla, Florian Cordes, Leif Christensen, Steffen Planthaber, Jan Albiez, Ingo Scholz, and Frank Kirchner. Towards a heterogeneous modular robotic team in a logistic chain for extraterrestrial exploration. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS2014)*, June 2014.

[7] Y. Nevatia, F. Bulens, J. Gancet, Y. Gao, S. Al-Mili, R. U. Sonsalla, T. P. Kaupisch, M. Fritsche, E. Allouis, T. Jorden, K. Skocki, S. Ransom, C. Saaj, M. Matthews, B. Yeomans, and L. Richter. Safe long-range travel for planetary rovers through forward sensing. In *Proceedings of the 12th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2013)*, Noordwijk, the Netherlands, May 2013.

[8] Roland U. Sonsalla, Yashodhan Nevatia, Martin Fritsche, Joel Bessekon Akpo, Jeremi Gancet, and Frank Kirchner. Design of a high mobile micro rover within a dual rover configuration for autonomous operations. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS2014)*, June 2014.

[9] E. Allouis, R. Marc, J. Gancet, R.U Sonsalla, J. Machowinski, T. Vogele, F.Comin, W. Lewinger, B. Yeomans, C. Saaj, P. Weclewski, K. Skocki, B. Imhof, S. Ransom, and L. Richter. Fp7 faster project - demonstration of multi-platform operation for safer planetary traverses. In *Proceedings of the 13th Symposium on Advanced Space Technoligies in Robotics and Automation (ASTRA-2015)*, May 2015.

[10] Markus Eich, Felix Grimminger, and Frank Kirchner. A versatile stair-climbing robot for search and rescue applications. In *Proceedings of the 2008 IEEE, International Workshop on Safty, Security and Rescue Robotics*, Sendai, Japan, 2008.

[11] Ajish Babu, Sylvain Joyeux, Jakob Schwendner, and Felix Grimminger. Effects of wheel synchronisation for the hybrid leg-wheel robot asguard. In *Proceedings of International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS-10)*, Sapporo, August 2010.

[12] Florian Cordes, Christian Oekermann, Ajish Babu, Daniel Kühn, Tobias Stark, and Frank Kirchner. An active suspension system for a planetary rover. In *Proceedings of the International Symposium in Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS2014)*, June 2014.

[13] Wiebke Wenzel, Florian Cordes, Alexander Dettmann, and Zhuowei Wang. Evaluation of a dust-resistant docking mechanism for surface exploration robots. In *Proceedings of the 15th International Conference on Advanced Robotics*, Tallinn, Estonia, June 2011.